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13. ABSTRACT *(Maximum 200 words)*

A parallel hole drilling device and a beam spread function (BSF) instrument were developed during the first year under this contract. A position indicator was added to the deployment package of the BSF and spectral radiometer packages. This allowed us to determine within millimeters the position relative to the ice surface. In cooperation with WETLabs Inc. we developed an in-ice spectral radiometer that makes measurements of azimuthally averaged irradiances at 28 wavelength bands in the visible portion of the spectrum. The large dynamic range of the instrument allowed measurements to be performed under bright sky to heavy overcast sky conditions. We participated in three major experimental studies of the optical properties of sea ice near Barrow, Alaska. These experiments included many other EMPOSI ARI investigators who studied the physical and biological nature of the ice as well as optical measurements from the ultraviolet to microwave portions of the spectrum. We also measured the diffuse attenuation coefficient in holes drilled at a number of angles relative to the surface, as well as utilizing a number of surface irradiance conditions from direct sun on bare ice to diffuse light through a snow pack on the ice. We also worked closely with WETLabs Inc. in developing an optical frazil meter. We worked in conjunction with the Army Cold Regions Research and Engineering Laboratory (CRREL) Ice Engineering Division in the calibration of the optical frazil meter. We measured frazil concentrations during the laboratory experiment to investigate the electromagnetic signature of frazil and the evolution into pancake ice.

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FINAL TECHNICAL REPORT

ONR GRANT #N00014-93-1-1024

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This final report covers the first three years of our participation in the "Sea Ice Electromagnics" ARI. The final two years are covered by a separate grant.

LONG-TERM GOALS:

The long-term goals of this program are; to study the relationship between the optical properties and physical characteristics of the sea ice, and to provide an inverse model to be able to derive the inherent optical properties from the apparent optical properties.

SCIENTIFIC AND TECHNOLOGICAL OBJECTIVES OF THIS EFFORT

Sea ice in its many stages of growth from frazil to multi-year ice affects the optics of the polar regions. To understand how the optical characteristics are affected by the physical and biological characteristics of the ice we have developed and utilized several optical measurement techniques. Technical objectives of this effort included the development of an in-ice spectral radiometer for measurement of the diffuse attenuation coefficient. We also developed and calibrated an optical instrument for the measurement of frazil ice concentrations. The scientific objectives were to make in-ice measurements of the beam spread function (BSF) using an instrument developed under this grant, the spectral diffuse attenuation coefficient, and the diffuse attenuation coefficient of a beam source. These measurements are to study the effects of the anisotropic nature of sea ice on the directional optical properties and to be used in determining the asymptotic diffuse attenuation coefficient.

A further objective of this study is to make detailed measurements of the radiance field within sea ice along with concurrent measurements of the physical and biological characteristics of the ice. The radiance measurements are necessary for our objectives to test forward radiative transfer models and to develop inverse models.

APPROACH:

To measure the radiance as a function of depth, zenith, and azimuthal angles a series of holes are drilled into the ice. Each hole corresponds to a particular zenith and azimuthal angle combination. Once the holes are drilled we insert the spectroradiometer detector head and vertical profiles of the radiance perpendicular to the direction of the hole is measured. The first hole drilled is vertical and later holes are drilled at shallower angles to ensure the detector head is always looking towards undisturbed ice.

To understand how the light field within the ice depends on the properties within the ice we are integrating the field measurements that we collected with measurements of the ice characteristics as well as integrating the data into radiative transfer models. We have collaborated with Drs. Perovich and Roesler to combine optical, physical, and biological measurements to fully characterize the ice and its related optical

properties. To further optical models of sea ice we have been collaborating with Drs. Jin and Stamnes to test their radiative transfer model and its associated optical property model. The data has also been provided to other investigators within the ARI for development and testing of optical and radiative transfer models.

TASKS COMPLETED AND TECHNICAL ACCOMPLISHMENTS

A parallel hole drilling device and a BSF instrument were developed during the first year under this contract. Subsequent modifications to the drill rig allowed for faster mast operation and eased the core removal process. These modifications shortened the time required to obtain a core. A position indicator was added to the deployment package of the BSF and spectral radiometer packages. This allowed us to determine within millimeters the position relative to the ice surface.

In cooperation with WETLabs Inc. we developed an in-ice spectral radiometer that makes measurements of azimuthally averaged irradiances at 28 wavelength bands in the visible portion of the spectrum. The large dynamic range of the instrument allowed measurements to be performed under bright sky to heavy overcast sky conditions.

We participated in three major experimental studies of the optical properties of sea ice near Barrow, Alaska. These experiments included many other EMPOSI ARI investigators who studied the physical and biological nature of the ice as well as optical measurements from the ultraviolet to microwave portions of the spectrum. Measurements of the BSF through horizontal sections of the ice were made in two manners. One method held the source and detector package at a constant depth and the source was rotated horizontally. In the other method the source was held at a constant depth and the detector package was vertically profiled some distance from the source. We also measured the diffuse attenuation coefficient in holes drilled at a number of angles relative to the surface, as well as utilizing a number of surface irradiance conditions from direct sun on bare ice to diffuse light through a snow pack on the ice. Changes in the detector configuration were accomplished by masking portions of the detector sphere. We also worked closely with WETLabs Inc. in developing an optical frazil meter. We worked in conjunction with the Army Cold Regions Research and Engineering Laboratory (CRREL) Ice Engineering Division in the calibration of the optical frazil meter.

We measured frazil concentrations during the laboratory experiment to investigate the electromagnetic signature of frazil and the evolution into pancake ice.

RESULTS

Measurement of the BSF while holding the source and detector at a fixed depth showed that the BSF was strongly affected by the degree of crystal alignment (Figure 1). This series of measurements also provides an indication that the anisotropic crystal alignment affects the propagation of a beam differently depending on the orientation of the beam to the crystal faces. Measurement of the BSF by vertically profiling the detector past the source showed many patterns indicating the very complex nature of the propagation of a narrow beam of light. The BSF patterns observed include a symmetric maximum at the source depth, a skewed maximum, and multiple local maxima. In some instances there is evidence of light piping causing the beam to propagate more favorably at a fixed depth in the ice (Figure 2).

Measurements with the spectral radiometer show large differences in diffuse attenuation in the surface layer at two sites approximately 20 km apart. These differences are related to the absorbing materials contained in the ice surface and the differences in the near surface crystal structure. Deeper within the ice at the two locations the physical and biological properties are similar to each other and the attenuation coefficients are similar (Figure 3).

The calibration of the frazil ice meter indicated excellent agreement between ice concentration estimates based on our differential absorption technique and estimates based on thermodynamics.

During the second sea-ice experiment, radiance measurements in first year ice were made at two locations approximately 30 m apart. In both profiles of the horizontal radiance there is evidence of small scale structure strongly influencing the propagation of light (Figure 4). The strong feature at 0.2 m depth was also observed in ice slabs quarried within the sampling region by Drs. Shapiro and Cole. Not all of the features in the radiance profile are determined by the physical characteristics of the ice. The larger scale (10 cm) features are found to be strongly correlated to the absorption by the inclusions (Figure 5). While the magnitude of the attenuation values depend on many conditions there is apparently at least one spectral quality common to the first year ice at all sites. At the sites where measurements were made the attenuation of the red light is relatively highest at the upper surface. Within the ice the attenuation spectrum becomes more flat with depth (Figure 6).

Two of the conditions that we intended to determine were; if the light field was isotropic, and at what depth does the light field reach an asymptotic state. The radiance at two zenith angles is given in Figure 7 and the figure shows that the light field within ice is not isotropic. To test if the asymptotic state is reached we use the requirement that the radiance attenuation at all angles is equal. It can be seen from the attenuation calculations presented in Figure 8 that at depth greater than 0.25 m the attenuation is nearly the same at the two angles. When the asymptotic condition is met then the relationships between the inherent and apparent optical properties in this region can be used to invert the measured radiance profiles to obtain the inherent optical properties.

Analysis of these results and subsequent publication will take place during the final two years of our participation in the Sea Ice Electromagnics ARI.

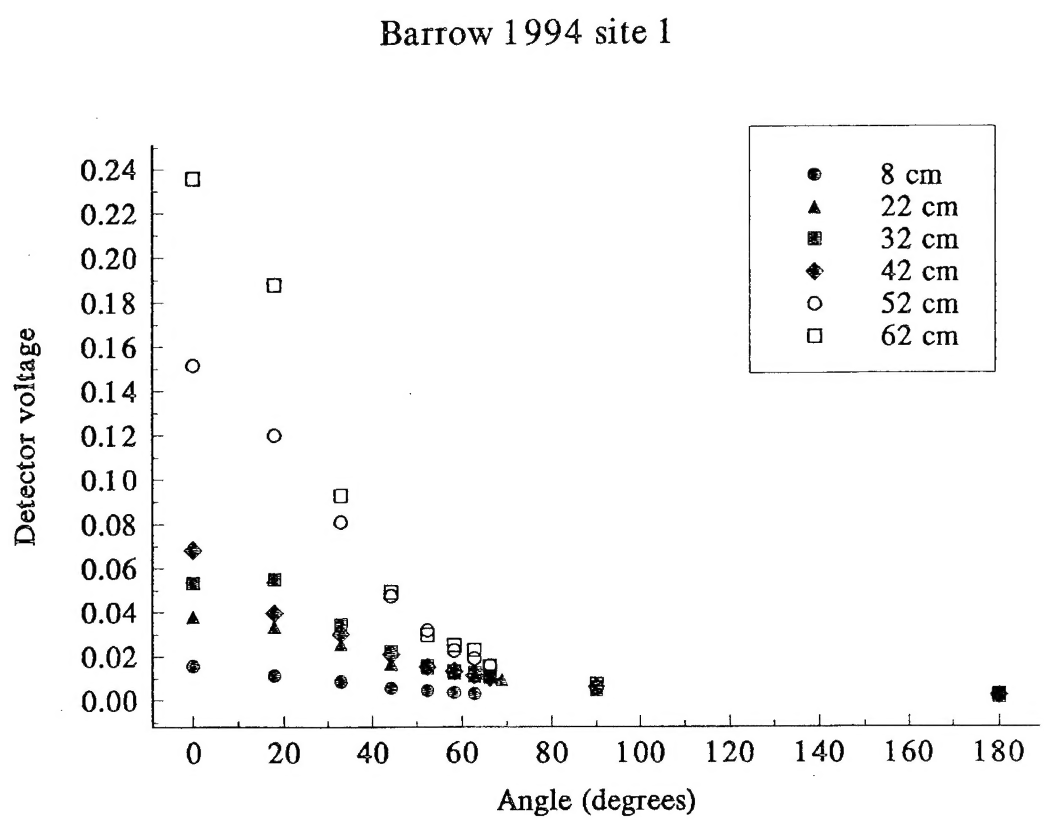

Figure 1 BSF measurements made at a number of depths within first year sea ice off of Barrow, Alaska. The ice crystals in this region became larger and more uniformly aligned with depth. Note that in the unaligned region near the surface the BSF is relatively flat compared to deeper in the ice where the ice crystals were more aligned.

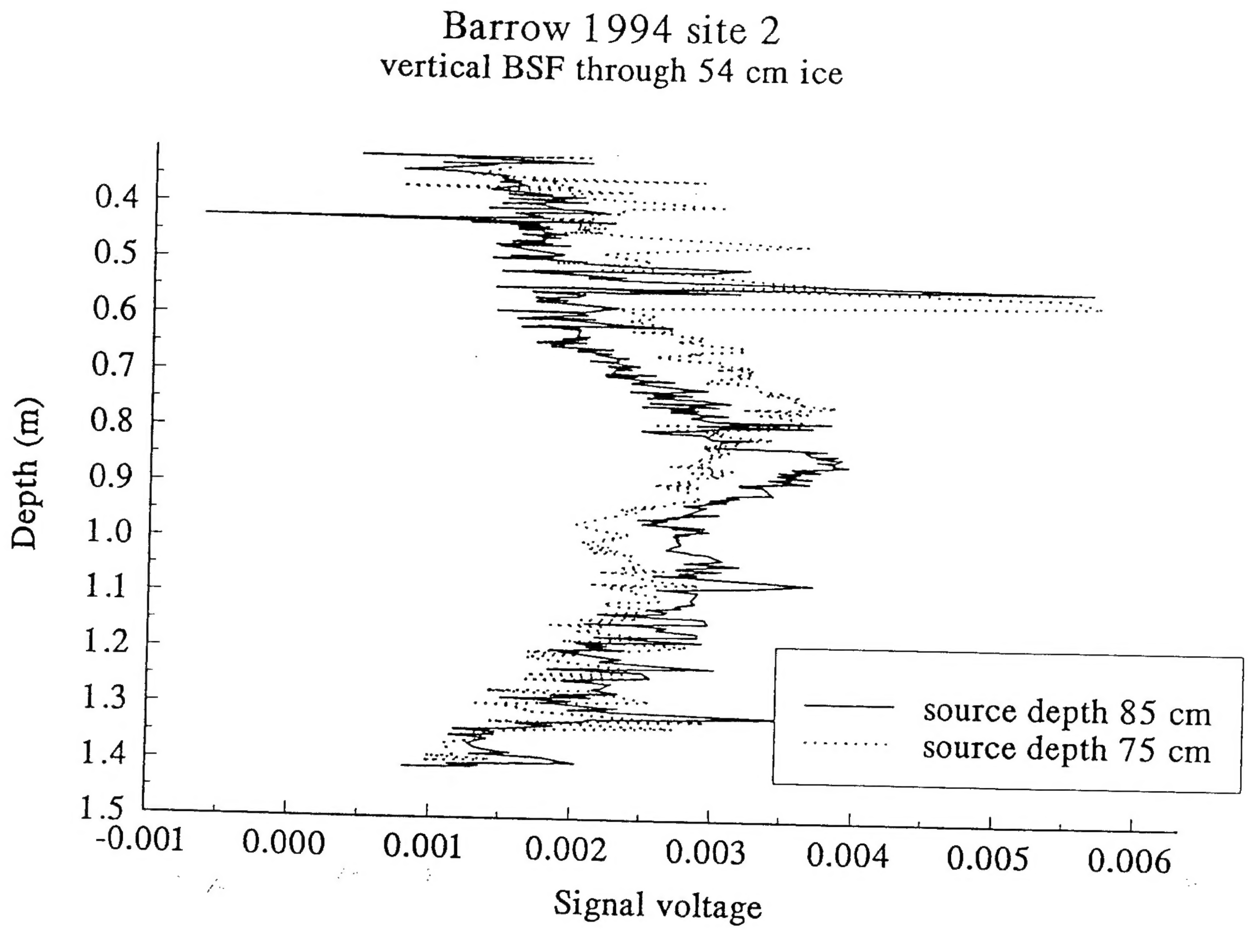

Figure 2 BSF measurements made while holding the source at fixed depths within the ice and vertically profiling the detector. The ice web between holes was 54 cm for this case. A broad maximum in detector voltage is found at the same level as the source beam. There is a dominant maximum located at a fixed depth in the ice for two different source locations. Many of the other characteristics of the profiles appear to be controlled by location in the ice rather than by the position of the source.

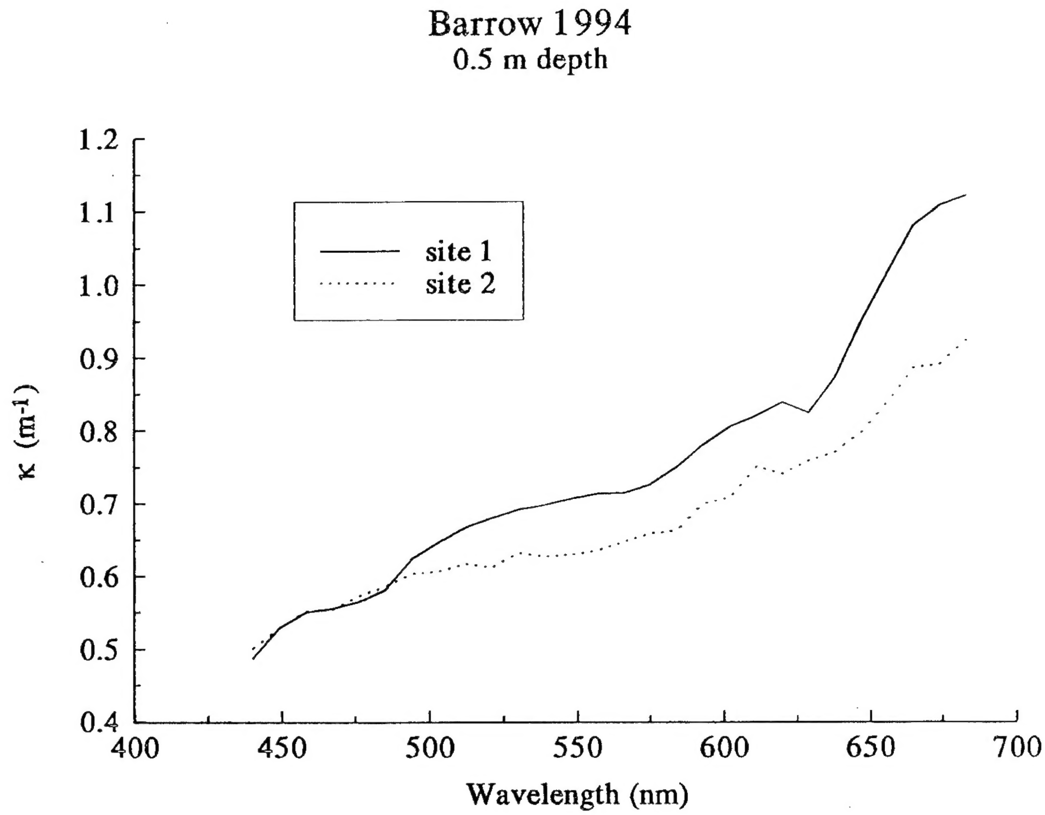

Figure 3 The spectral diffuse attenuation coefficient at 0.5 m ice depth for the detector arrangement used during the Barrow experiment. These measurements are made in holes drilled perpendicular to the ice surface. The detector was a spherical collector with plates above and below the sphere to block light propagating along the axis of the hole. At 0.5 m in the ice the physical and biological properties between sites are similar. The optical properties are also seen to be similar.

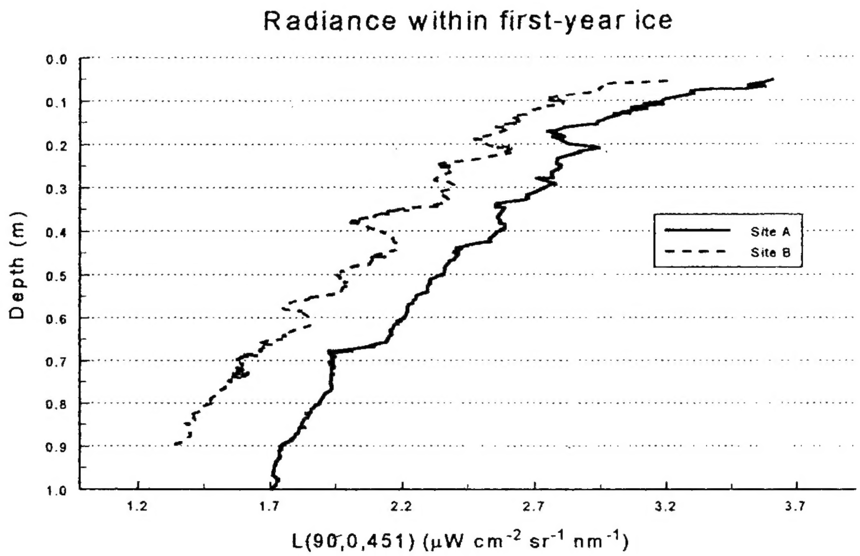

Figure 4. The horizontal radiance measured at two locations in first year sea ice. Both profiles exhibit structure in the light field that is related to the characteristics of the ice. The horizontal persistence of the layer at 0.2 m makes it well suited for comparison with physical measurements taken within the area.

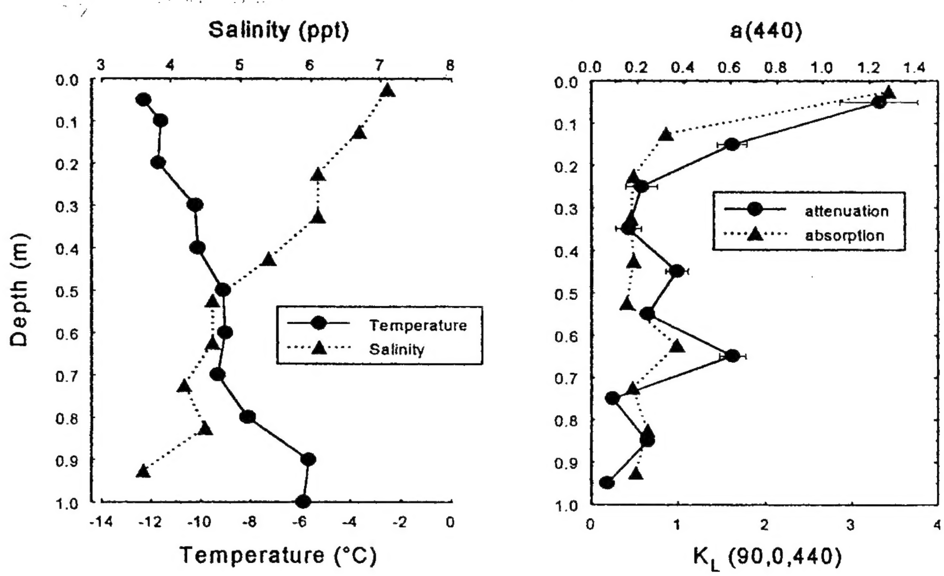

Figure 5. The temperature, salinity, and absorption profiles are used to characterize the ice. The attenuation of light measured at 90° shows strong correlation to the vertical structure of the absorbing components.

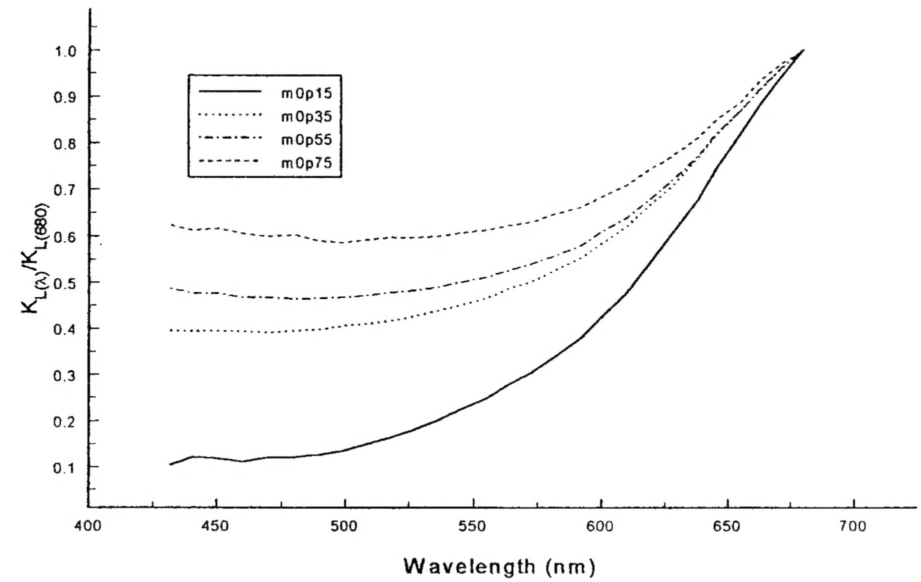

Figure 6. The spectral radiance attenuation normalized to the value at 680 nm. At the upper surface the blue to red attenuation ratio is lowest and the relative attenuation spectrum flattens with depth.

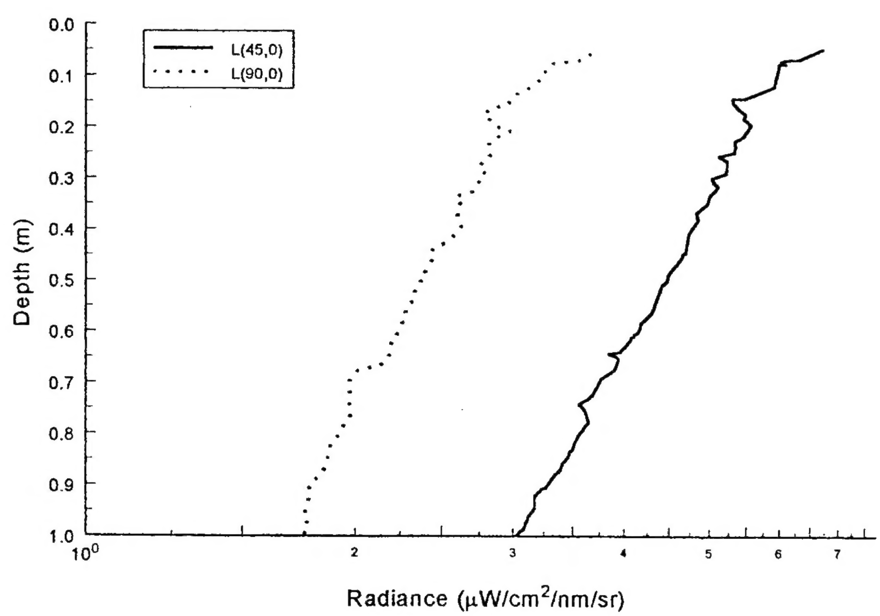

Figure 7. Radiance measured at 451 nm and at two zenith angles. The difference in the radiance values demonstrates that the light field is not isotropic.

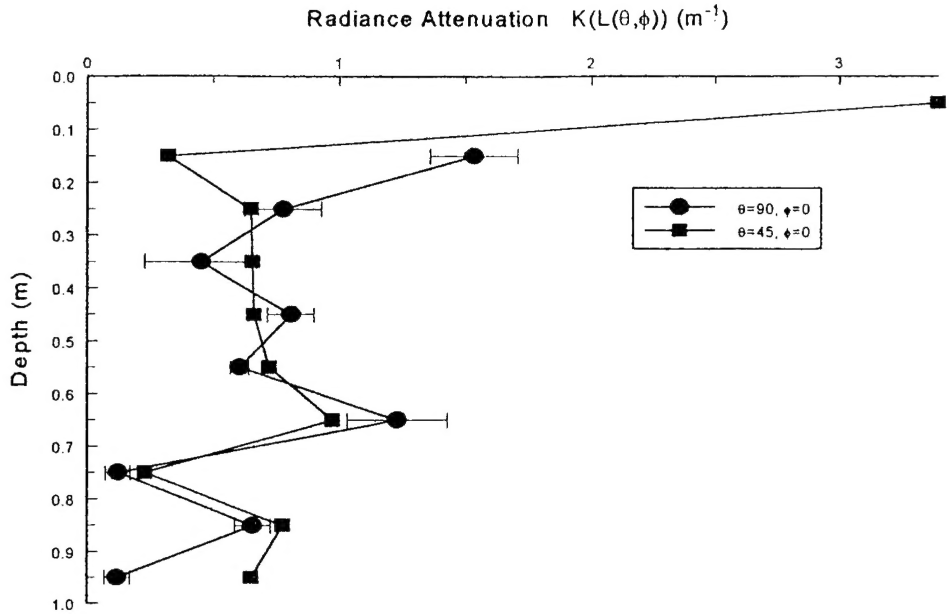

Figure 8. The attenuation values calculated on 10 cm intervals of the radiance given in the above figure provide an indication that the light field is near asymptotic at depths of 0.25 m.